

The Exclusive Drell-Yan Process and Deeply Virtual Pion Production

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In this talk it is reported on analyses of $p \rightarrow l\pi^+n$ and $\pi^-p \rightarrow l^+l^-n$ within the handbag approach. It is argued that recent measurements of hard pion production performed by HERMES and CLAS clearly indicate the occurrence of strong contributions from transversely polarized photons. The $\gamma_T^* \rightarrow \pi$ transitions are described by the transversity GPDs accompanied by twist-3 pion wave functions. The experiments also require strong contributions from the pion pole which can be modeled as classical one-pion exchange. With these extensions the handbag approach leads to results on cross sections and spin asymmetries in fair agreement with experiment. This approach is also used for an estimate of the partial cross sections for the exclusive Drell-Yan process.

KEYWORDS: Pion production, factorization, twist-3, transversity, Drell-Yan process

1. Introduction

The handbag approach offers a partonic description of many hard exclusive processes. It is based on factorization in hard subprocesses and soft hadronic matrix elements, the so-called generalized parton distributions (GPDs). This approach has been applied by now to many deeply virtual and wide-angle processes and even to the exclusive production of hardons involving heavy quarks. Here in this talk, the interest is focused on exclusive pion leptonproduction, $lp \rightarrow l\pi^+n$, and the exclusive pion-induced Drell-Yan process, $\pi^-p \rightarrow l^+l^-n$.

For pion leptonproduction there is a rigorous proof [1] of collinear factorization of the process amplitudes for longitudinally polarized virtual photons, γ_L^* , in a hard partonic subprocess and GPDs in the generalized Bjorken regime of large photon virtuality, Q^2 , and large photon-proton center of mass energy, W , but small invariant momentum transfer, $-t$. It however turned out that leading-twist calculations underestimate the experimental pion production cross section by order of magnitude. It became evident as I am going to demonstrate in Sect. 2, the pion pole is to be treated as a classical one-particle exchange rather than as a part of the GPD \tilde{E} . Moreover, experiments tell us that there are strong, for π^0 production even dominant, contribution from transversely polarized photons, γ_T^* .

The high-energy pion beam at J-PARC offers the possibility of measuring the exclusive Drell-Yan process which is closely related to pion leptonproduction. The same GPDs contribute and the subprocesses are $\hat{s}-\hat{u}$ crossed ones (\hat{s} and \hat{u} are the subprocess Mandelstam variables):

$$\mathcal{H}^{\pi^- \rightarrow \gamma^*}(\hat{u}, \hat{s}) = -\mathcal{H}^{\gamma^* \rightarrow \pi^+}(\hat{s}, \hat{u}). \quad (1)$$

Eq. (1) is equivalent to the replacement of the space-like photon virtuality, Q^2 , by minus the time-like one, Q'^2 . Since leading-twist calculations of pion production underestimates experiment by far it is plausible to expect a similar failure for the Drell-Yan process. As advocated for in [2], one may rather apply that what has been learned in the analysis of pion

production also to the Drell-Yan process. In Sect. 3 it is reported on such an analysis. Future data on the exclusive Drell-Yan process may reveal whether or not our present understanding of hard exclusive process in terms of convolutions of GPDs and hard scatterings also holds for time-like photons. This is a non-trivial issue because the physics in the time-like region is complicated and often not well understood.

2. Leptoproduction of pions

The leading-twist helicity amplitudes for pion production read

$$\begin{aligned}\mathcal{M}_{0+,0+} &= \frac{e_0}{Q} \sqrt{1-\xi^2} \int_{-1}^1 dx \mathcal{H}_{0+0+} \left[\tilde{H} - \frac{\xi^2}{1-\xi^2} \tilde{E} \right], \\ \mathcal{M}_{0-,0+} &= \frac{e_0}{Q} \frac{\sqrt{-t'}}{2m} \xi \int_{-1}^1 dx \mathcal{H}_{0+0+} \tilde{E},\end{aligned}\tag{2}$$

where \mathcal{H}_{0+0+} denotes the subprocess amplitude and \tilde{H}, \tilde{E} the relevant GPDs. The nucleon mass is denoted by m . The skewness, ξ , is related to Bjorken- x by $\xi = x_B/(1-x_B)$ up to corrections of order $1/Q^2$. In (2) the usual abbreviation $t' = t - t_0$ is employed where the minimal value of $-t$ corresponding to forward scattering, is $t_0 = -4m^2\xi^2/(1-\xi^2)$. Helicities are labeled by their signs or by zero; they appear in the familiar order: pion, outgoing nucleon, photon, ingoing nucleon.

Power corrections to the leading-twist result (2) are theoretically not under control. It is therefore not clear at which values of Q^2 and W the amplitudes (2) can be applied. The onset of the leading-twist dominance has to be found out by comparison with experiment. An example of power corrections is set by the $\gamma_T^* \rightarrow \pi$ amplitudes which are theoretically suppressed by $1/Q$ as compared to the $\gamma_L^* \rightarrow \pi$ amplitudes. Still, as experiments tell us, the $\gamma_T^* \rightarrow \pi$ amplitudes play an important role in hard exclusive pion leptoproduction. The first experimental evidence for strong contribution from $\gamma_T^* \rightarrow \pi$ transitions came from the spin asymmetry, A_{UT} , measured with a transversely polarized target by the HERMES collaboration for π^+ production [3]. Its $\sin\phi_s$ modulation where the angle ϕ_s defines the orientation of the target spin vector, unveils a particularly striking behavior: It is rather large and does not show any indication of a turnover towards zero for $t' \rightarrow 0$. For $t' \rightarrow 0$ $A_{UT}^{\sin\phi_s}$ is under control of the interference term

$$A_{UT}^{\sin\phi_s} \propto \text{Im} \left[\mathcal{M}_{0-,++}^* \mathcal{M}_{0+,0+} \right].\tag{3}$$

Both the amplitudes are not forced by angular momentum conservation to vanish in the limit $t' \rightarrow 0$. Hence, the small $-t'$ behavior of the $A_{UT}^{\sin\phi_s}$ data entails a sizeable $\gamma_T^* \rightarrow \pi$ amplitude.

A second evidence for large contributions from transversely polarized photons comes from the CLAS measurement [4] of the π^0 electroproduction cross sections. As can be seen from Fig. 1 the transverse-transverse interference cross section is negative and amounts to about 50% of the unseparated cross section in absolute value.

2.1 Transversity

The question is whether or not the handbag approach can be generalized in order to account also the $\gamma_T^* \rightarrow \pi$ amplitudes. In Fig. 2 a typical Feynman graph for pion production is depicted with helicity labels for the amplitude $\mathcal{M}_{0-,++}$. Angular momentum conservation forces the subprocess amplitude as well as the nucleon-parton matrix element to vanish $\propto \sqrt{-t'}$ for $t' \rightarrow 0$ for any contribution to $\mathcal{M}_{0-,++}$ from the usual helicity non-flip GPDs \tilde{H}

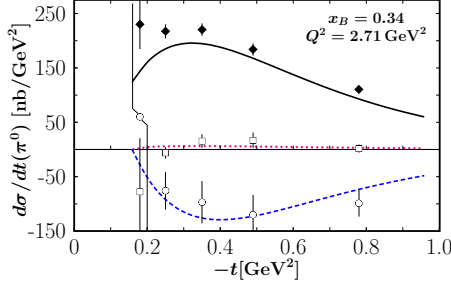


Fig. 1. The unseparated (long.-transv., transv.-transv.) cross section. Data [4] are shown as diamonds (squares, circles). The theoretical results are taken from [6].

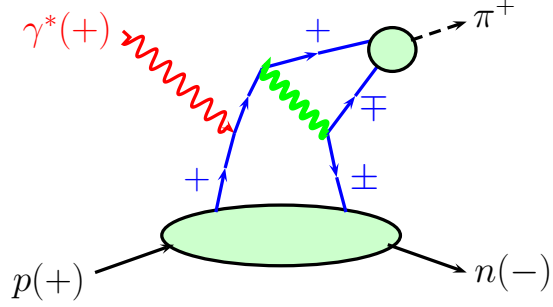


Fig. 2. A typical lowest-order Feynman graph for pion leptonproduction. The signs indicate the helicities of the involved particles.

and \tilde{E} . This result is in conflict with the HERMES data on $A_{UT}^{\sin\phi_s}$. In [5, 6] (see also [7]), it has been suggested that contributions from the transversity GPDs, for which the emitted and reabsorbed partons have opposite helicities, are responsible for the above mentioned experimental phenomena. Factorization of the $\gamma_T^* \rightarrow \pi$ amplitudes is assumed. The dominant contributions from the transversity GPDs are ($\tilde{E}_T = 2\tilde{H}_T + E_T$)

$$\begin{aligned}\mathcal{M}_{0+, \mu+} &= e_0 \frac{\sqrt{-t'}}{4m} \int_{-1}^1 dx \mathcal{H}_{0-, ++} \tilde{E}_T, \\ \mathcal{M}_{0-, ++} &= e_0 \sqrt{1 - \xi^2} \int_{-1}^1 dx \mathcal{H}_{0-, ++} H_T, \\ \mathcal{M}_{0-, -+} &= 0.\end{aligned}\tag{4}$$

The neglect of the other transversity GPDs is justified at least at small ξ and $-t'$. As we will see these amplitudes meet the main features of the experimental data mentioned above.

2.2 The subprocess amplitude $\mathcal{H}_{0-, ++}$

As can be seen from Fig. 2 quark and antiquark forming the pion have the same helicity for $\mathcal{H}_{0-, ++}$. Hence, a twist-3 pion wave function is required. There are two twist-3 distribution amplitudes, a pseudoscalar one, Φ_P and a pseudotensor one, Φ_σ . Assuming the three-particle contributions to be strictly zero, the twist-3 distribution amplitudes are given by [8]

$$\Phi_P \equiv 1 \quad \Phi_\sigma = 6\tau(1 - \tau)\tag{5}$$

Here τ is the momentum fraction the quark in the pion carries with respect to the pion momentum. The subprocess amplitude $\mathcal{H}_{0-, ++}$ is computed to lowest-order of perturbation theory. It turns out that the pseudotensor contribution is proportional to t/Q^2 and consequently neglected. The pseudoscalar term is non-zero at $t = 0$ but infrared singular. In order to regularize this singularity the modified perturbative approach is used in [5, 6] in which quark transverse momentum, k_\perp , are retained in the subprocess whereas the emission and reabsorption of partons from the nucleons is assumed to happen collinear to the nucleon momenta [9]. In this approach the subprocess amplitude for π^+ production reads

$$\mathcal{H}_{0-, ++} = \frac{2}{\pi^2} \frac{C_F}{\sqrt{2N_C}} \mu_\pi \int d\tau d^2\mathbf{k}_\perp \Psi_{\pi P}(\tau, k_\perp) \alpha_s(\mu_R)$$

$$\times \left[\frac{e_u}{x - \xi + i\epsilon} \frac{1}{\bar{\tau} \frac{x-\xi}{2\xi} Q^2 - k_\perp^2 + i\epsilon} - \frac{e_d}{x + \xi - i\epsilon} \frac{1}{-\tau \frac{x+\xi}{2\xi} Q^2 - k_\perp^2 + i\epsilon} \right]. \quad (6)$$

For the case of the π^0 the quark charges have to be taken out; they appear in the flavor combination of the GPDs. The pion light-cone wave function, $\Psi_{\pi P}$, is parametrized as

$$\Psi_{\pi P} = \frac{16\pi^{3/2}}{\sqrt{2N_C}} f_\pi a_P^3 |\mathbf{k}_\perp| \exp[-a_P^2 k_\perp^2]. \quad (7)$$

Its associated distribution amplitude is the pseudoscalar one given in (5). For the transverse-size parameter, a_P , the value 1.8 GeV is adopted and $f_\pi (= 0.132 \text{ GeV})$ denotes the pion decay constant. The parameter μ_π in (6) is related to the chiral condensate

$$\mu_\pi = \frac{m_\pi^2}{m_u + m_d} \quad (8)$$

where m_π is the pion mass and m_u, m_d current quark masses. In [5, 6] a value of 2 GeV² is taken for μ_π . The contributions from transversely polarized photons are parametrically suppressed by μ_π/Q as compared to the $\gamma_L^* \rightarrow \pi$ amplitudes (2). However, for values of Q accessible in current experiments, μ_π/Q is of order 1.

The amplitude (6) is Fourier transformed to the impact parameter space and the integrand is multiplied by a Sudakov factor, $\exp[-S]$, which represents gluon radiation in next-to-leading-log approximation using resummation techniques and having recourse to the renormalization group [10]. The Sudakov factor cuts off the b -integration at $b_0 = 1/\Lambda_{\text{QCD}}$. In the modified perturbative approach the renormalization and factorization scales are $\mu_R = \max[\tau Q, (1 - \tau)Q, 1/b]$ and $\mu_F = 1/b$, respectively. In [5, 6] the modified approach is also applied to the $\gamma_L^* \rightarrow \pi$ amplitudes. The Sudakov factor guarantees the emergence of the twist-2 result for $Q^2 \rightarrow \infty$.

2.3 The pion pole

A special feature of π^+ production is the appearance of the pion pole. As has been shown in [11] the pion pole is part of the GPD \tilde{E}

$$\tilde{E}_{\text{pole}}^u = -\tilde{E}_{\text{pole}}^d = -\Theta(\xi - |x|) \frac{m f_\pi g_{\pi NN}}{\sqrt{2}\xi} \frac{F_{\pi NN}(t)}{t - m_\pi^2} \Phi_\pi\left(\frac{x + \xi}{2\xi}\right) \quad (9)$$

The coupling of the exchanged pion to the nucleons is described by the coupling constant $g_{\pi NN} (= 13.1 \pm 0.2)$ and a form factor parametrized as a monopole with a parameter $\Lambda_N (= 0.44 \pm 0.07)$; F_π denotes the electromagnetic form factor of the pion. The convolution of \tilde{E}_{pole} with the subprocess amplitude $\mathcal{H}_{0\lambda,0\lambda}$ can be worked out analytically. The contribution of the pion pole to the longitudinal cross section is

$$\frac{d\sigma_L^{\text{pole}}}{dt} \sim \frac{-t Q^2}{(t - m_\pi^2)^2} \left[e_0 g_{\pi NN} F_{\pi NN}(t) F_\pi^{\text{pert}}(Q^2) \right]^2. \quad (10)$$

Here, F_π^{pert} is the leading-order perturbative contribution to F_π which is known to underestimate the experimental form factor [12] substantially, and consequently (10) is much smaller than data on the π^+ cross section, see Fig. 3. In [5, 6] the perturbative result for F_π was therefore replaced by its experimental value. This prescription is equivalent to computing the pion pole contribution as a one-particle exchange. With this replacement one sees that the pole term controls the π^+ cross section at small $-t'$, see Fig. 3. A detailed discussion of the pion pole contribution can be found in [14]. It also plays a striking role in electroproduction of ω mesons [15] where it dominantly contributes to the amplitudes for transversely polarized ω mesons.

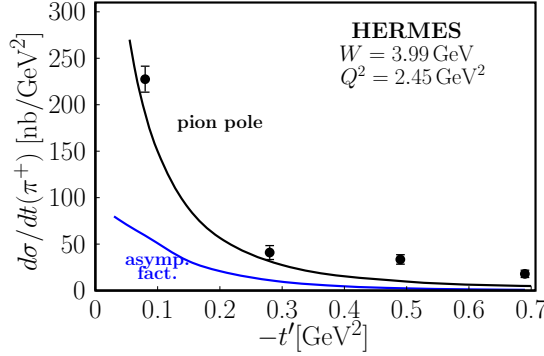


Fig. 3. The unseparated π^+ cross section versus $-t'$. The lines represent the pion-pole contribution (10) with F_{π}^{pert} replaced by F_{π}^{exp} and the leading-twist result. Data taken from [13].

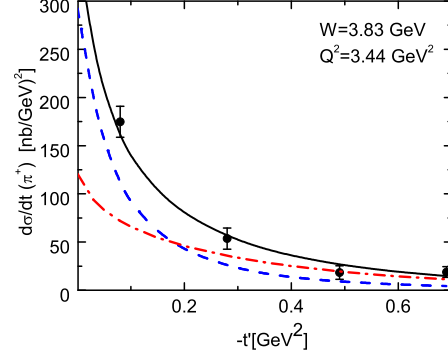


Fig. 4. The unseparated π^+ cross section. Data taken from [13]. The solid (dashed, dash-dotted) curve represents the results of [5] for the unseparated (longitudinal, transverse) cross section.

2.4 Phenomenology

In order to make predictions and comparison with experiment the GPDs are needed. In [5, 6, 9] the GPDs are constructed with the help of the double-distribution representation. According to [16] a double distribution is parametrized as a product of a zero-skewness GPD and an appropriate weight function that generates the skewness dependence. The zero-skewness GPD itself is composed of its forward limit, $K(x, \xi = t = 0) = k(x)$, multiplied by an exponential in t with a profile function, $f(x)$, parametrized in a Regge-like manner

$$f(x) = -\alpha' \ln x + B \quad (11)$$

at small $-t$. The GPD \tilde{H} at $\xi = 0$ is taken from a recent analysis of the nucleon form factors [17] while \tilde{E} is neglected. The forward limit of the GPD H_T is given by the transversity parton distributions, known from an analysis of the azimuthal asymmetry in semi-inclusive deep inelastic lepton-nucleon scattering and inclusive two-hadron production in electron-positron annihilations [18], but the normalization of H_T is adjusted to lattice QCD moments [19]. The forward limit of \bar{E}_T is parametrized like the usual parton densities

$$\bar{e}_T(x) = Nx^{-\alpha}(1-x)^{\beta} \quad (12)$$

with $\alpha = 0.3$ for both u and d quarks and $\beta^u = 4$, $\beta^d = 5$. The normalization as well as the parameters α' and B for each of the transversity GPDs are estimated by fits to the HERMES data on the π^+ cross section [13] and to lattice QCD results [20] on the moments of \bar{E}_T .

An example of the results for the π^+ cross section is shown in Fig. 4, typical results for π^0 production in Fig. 1. At small $-t'$ the π^+ cross section is under control of the pion pole as discussed in Sect. 3. The contribution from \tilde{H} to the longitudinal cross section is minor. The transverse cross section, although parametrically suppressed by μ_{π}^2/Q^2 , is rather large and even dominates for $-t' \gtrsim 0.2 \text{ GeV}^2$. It is governed by H_T , the contribution from \bar{E}_T is very small. This fact can easily be understood considering the relative sign of u and d quark GPDs. For H_T they have opposite signs but the same sign for \bar{E}_T . Moreover, \bar{E}_T^u and \bar{E}_T^d are of similar size. This pattern of these GPDs is supported by large- N_c considerations [21]. Since the GPDs contribute to π^+ production in the flavor combination

$$K^{\pi^+} = K^u - K^d \quad (13)$$

it is obvious that the contributions from \bar{E}_T^u and \bar{E}_T^d cancel each other to a large extent in contrast to those from H_T .

For π^0 production the situation is reversed since the GPDs appear now in the flavor combination

$$K^{\pi^0} = \frac{1}{\sqrt{2}}(e_u K^u - e_d K^d). \quad (14)$$

The contribution from \bar{E}_T makes up the transverse-transverse interference cross section whereas the transverse cross section receives contribution from both H_T and \bar{E}_T (see Eq. (4)):

$$\frac{d\sigma_T}{dt} = \frac{1}{\kappa} \left[\frac{1}{2} |\mathcal{M}_{0-,++}|^2 + |\mathcal{M}_{0+,++}|^2 \right] \quad \frac{d\sigma_{TT}}{dt} = -\frac{1}{\kappa} |\mathcal{M}_{0+,++}|^2 \quad (15)$$

where κ is a phase-space factor. However, the sum of these cross section is only fed by H_T . In [5, 6] it is predicted that for π^0 production

$$\frac{d\sigma_L}{dt} \ll \frac{d\sigma_T}{dt}. \quad (16)$$

Hence, to a good approximation the transverse cross section equals the unseparated one. The prediction (16) is consistent with the very small longitudinal-transverse interference cross section, see Fig. 1, and is confirmed by a recent Hall A measurement [22]. It is to be emphasized that this prediction is what is expected in the limit $Q^2 \rightarrow 0$ and not for $Q^2 \rightarrow \infty$.

The transversity GPDs play a similarly prominent role in leptonproduction of other pseudoscalar mesons. Consider, for example, η production. Under the plausible assumption $K^s = K^{\bar{s}}$ only the u and d -quark GPDs in the combination

$$K^\eta \simeq \frac{1}{\sqrt{6}}(e_u K^u + e_d K^d). \quad (17)$$

contribute to η production. With regard to the different signs in (17) and (14) it is evident that H_T plays a more important role for η than for π^0 production whereas for \bar{E}_T the situation is reversed with the consequence of an η/π^0 ratio of about 1 for $t' \rightarrow 0$ and a small ratio otherwise. The transverse-transverse cross section is now very small because of the strong cancellation between \bar{E}_T^u and \bar{E}_T^d . These properties of η production is in fair agreement with preliminary CLAS data [23].

3. The exclusive Drell-Yan process

Let me now turn to the Drell-Yan process. Leading-twist analyses have been performed in [24, 25]. It has been found that the longitudinal cross section amounts to a few pb/GeV² at small t' . With regard to the failure of leading-twist analyses of pion leptonproduction a reanalysis of the Drell-Yan process seems to be appropriate taking into account what has been learned from analyses of pion leptonproduction [2].

The cross section for the Drell-Yan process reads

$$\begin{aligned} \frac{d\sigma}{dtdQ'^2 d\cos\theta d\phi} &= \frac{3}{8\pi} \left\{ \sin^2\theta \frac{d\sigma_L}{dtdQ'^2} + \frac{1+\cos^2\theta}{2} \frac{d\sigma_T}{dtdQ'^2} \right. \\ &\quad \left. + \frac{\sin(2\theta)\cos\phi}{\sqrt{2}} \frac{d\sigma_{LT}}{dtdQ'^2} + \sin^2\theta \cos(2\phi) \frac{d\sigma_{TT}}{dtdQ'^2} \right\} \quad (18) \end{aligned}$$

where ϕ denotes the azimuthal angle between the lepton and the hadron plane and the angle θ defines the direction of the negatively charged lepton momentum in the rest frame

of the virtual photon. The four partial cross sections are analogously defined to those for pion leptonproduction. Their evaluation within the handbag approach is also analogous to pion production discussed in Sect. 1. The only new item in this evaluation is the time-like electromagnetic form factor of the pion replacing the space-like one. For $Q'^2 \geq 2 \text{ GeV}^2$ the average value of the data from CLEO [26], BaBar [27] and from the $J/\Psi \rightarrow \pi^+\pi^-$ decay [28]

$$Q'^2 |F_\pi(Q'^2)| = 0.88 \pm 0.04 \text{ GeV}^2. \quad (19)$$

For its phase, $\exp[i\delta(Q'^2)]$, it is relied on a recent dispersion analysis [29] which provides

$$\delta = 1.014\pi + 0.195(Q'^2/\text{GeV}^2 - 2) - 0.029(Q'^2/\text{GeV}^2 - 2)^2. \quad (20)$$

for $2 \text{ GeV}^2 \lesssim Q'^2 \lesssim 5 \text{ GeV}^2$. In the absence of any other information on this phase we use this parametrization up to $\approx 8.9 \text{ GeV}^2$ where $\delta = \pi$. For larger values of Q'^2 we take $\delta = \pi$, the asymptotic phase of the time-like pion form factor obtained by analytic continuation of the perturbative result for the space-like form factor.

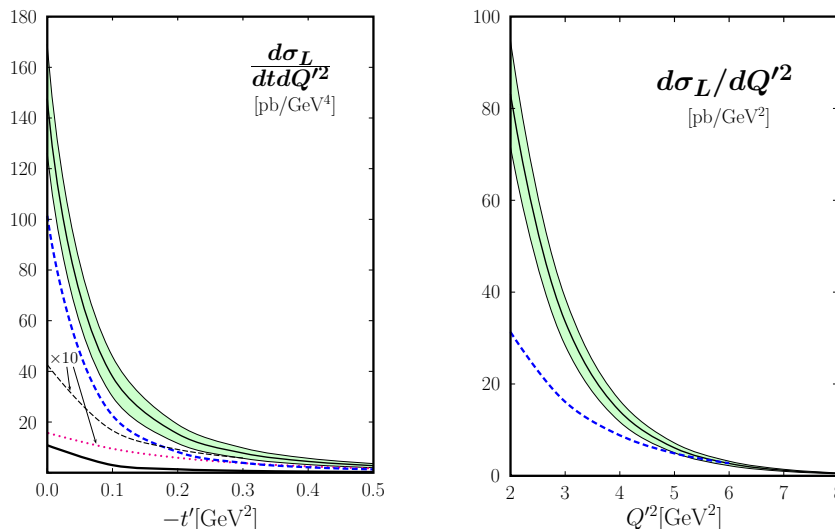


Fig. 5. The longitudinal cross sections $d\sigma_L/dtdQ'^2$ (left) at $Q'^2 = 4 \text{ GeV}^2$ versus t' and $d\sigma_L/dQ'^2$ (right) versus Q'^2 . The thin solid lines with error bands represent our full results at $s = 20 \text{ GeV}^2$, the thick dashed ones those at 30 GeV^2 . The thick solid (dotted, thin dashed) line is the interference term (contribution from $|\langle \tilde{H}^{(3)} \rangle|^2$, leading twist). The latter two results are multiplied by 10 for the ease of legibility.

In Fig. 5 predictions for the longitudinal cross sections are shown. They are markedly larger than the leading-twist results [24, 25]. This amplification is due to the use of the experimental value of the pion form factor (19) instead of its leading-twist result ($\approx 0.15 \text{ GeV}^2$). We stress that the OPE contribution from the pion pole does neither rely on QCD factorization nor on a hard scattering. It is therefore not subject to evolution and higher-order perturbative QCD corrections. In [2] predictions for the other partial cross sections are also presented. The transverse cross section, which amounts to about 25% of the longitudinal cross section, is dominated by the GPD H_T . The contribution from \bar{E}_T is tiny and, hence, $d\sigma_{TT}$. On the other hand, the longitudinal-transverse interference cross section is not small. The cross sections decrease with growing s . At, say, $s \approx 360 \text{ GeV}^2$ as is available from the pion beam at CERN, the longitudinal cross section is about 30 fb/GeV^2 at $Q'^2 = 4 \text{ GeV}^2$.

4. Summary

In this article it is reported on calculations of $lp \rightarrow l\pi^+n$ and $\pi^-p \rightarrow l^+l^-n$ within the handbag approach. Forced by experimental results on hard pion production two corrections to the leading-twist amplitudes are taken into account: the pion pole is treated as a one-pion exchange and amplitudes for transverse photons are added. These amplitudes are modeled by transversity GPDs in combination with a twist-3 pion wave function. With this generalized handbag approach reasonable agreement with the data on pion production is achieved. Future data on $\pi^-p \rightarrow l^+l^-n$, measured for instance at J-PARC may allow for a test of factorization in the time-like region. There is no proof for it but its validity seems to be plausible. However, Qiu [30] raised doubts on the factorization arguments for the exclusive Drell-Yan process.

The Drell-Yan process offers an opportunity to check the dependence of the $\pi\pi\gamma^*$ vertex on the pion virtuality by comparing data on the time-like pion form factor measured in $l^-l^+ \rightarrow \pi^-\pi^+$, with parametrizations of $\pi^-\pi^{*+} \rightarrow l^-l^+$ as part of the Drell-Yan amplitudes. The extraction of the space-like form factor from $lp \rightarrow l\pi^+n$ may benefit from that check.

References

- [1] J. C. Collins, L. Frankfurt and M. Strikman, Phys. Rev. D **56**, 2982 (1997).
- [2] S. V. Goloskokov and P. Kroll, Phys. Lett. B **748**, 323 (2015).
- [3] A. Airapetian *et al.* [HERMES Collaboration], Phys. Lett. B **682**, 345 (2010).
- [4] I. Bedlinskiy *et al.* [CLAS Collaboration], Phys. Rev. C **90**, no. 2, 025205 (2014) [Phys. Rev. C **90**, no. 3, 039901 (2014)].
- [5] S. V. Goloskokov and P. Kroll, Eur. Phys. J. C **65**, 137 (2010).
- [6] S. V. Goloskokov and P. Kroll, Eur. Phys. J. A **47**, 112 (2011).
- [7] G. R. Goldstein, J. O. Gonzalez Hernandez and S. Liuti, Phys. Rev. D **91**, no. 11, 114013 (2015).
- [8] V. M. Braun and I. E. Filyanov, Z. Phys. C **48**, 239 (1990) [Sov. J. Nucl. Phys. **52**, 126 (1990)] [Yad. Fiz. **52**, 199 (1990)].
- [9] S. V. Goloskokov and P. Kroll, Eur. Phys. J. C **53**, 367 (2008).
- [10] H. n. Li and G. F. Sterman, Nucl. Phys. B **381**, 129 (1992).
- [11] L. Mankiewicz, G. Piller and A. Radyushkin, Eur. Phys. J. C **10**, 307 (1999).
- [12] H. P. Blok *et al.* [Jefferson Lab Collaboration], Phys. Rev. C **78**, 045202 (2008).
- [13] A. Airapetian *et al.* [HERMES Collaboration], Phys. Lett. B **659**, 486 (2008).
- [14] L. Favart, M. Guidal, T. Horn and P. Kroll, Eur. Phys. J. A **52**, no. 6, 158 (2016).
- [15] S. V. Goloskokov and P. Kroll, Eur. Phys. J. A **50**, no. 9, 146 (2014).
- [16] I. V. Musatov and A. V. Radyushkin, Phys. Rev. D **61**, 074027 (2000).
- [17] M. Diehl and P. Kroll, Eur. Phys. J. C **73**, no. 4, 2397 (2013).
- [18] M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, A. Prokudin and S. Melis, Nucl. Phys. Proc. Suppl. **191**, 98 (2009).
- [19] M. Gockeler *et al.* [QCDSF and UKQCD Collaborations], Phys. Lett. B **627**, 113 (2005).
- [20] M. Gockeler *et al.* [QCDSF and UKQCD Collaborations], Phys. Rev. Lett. **98**, 222001 (2007).
- [21] P. Schweitzer and C. Weiss, PoS QCDEV **2015**, 041 (2015).
- [22] M. Defurne *et al.*, arXiv:1608.01003 [hep-ex].
- [23] V. Kubarovsky [for the CLAS Collaboration], Int. J. Mod. Phys. Conf. Ser. **40**, 1660051 (2016).
- [24] E. R. Berger, M. Diehl and B. Pire, Phys. Lett. B **523**, 265 (2001).
- [25] T. Sawada, W. C. Chang, S. Kumano, J. C. Peng, S. Sawada and K. Tanaka, Phys. Rev. D **93**, no. 11, 114034 (2016).
- [26] K. K. Seth, S. Dobbs, Z. Metreveli, A. Tomaradze, T. Xiao and G. Bonvicini, Phys. Rev. Lett. **110**, no. 2, 022002 (2013).
- [27] B. Aubert *et al.* [BaBar Coll.], Phys. Rev. Lett. **103**, 231801 (2009).
- [28] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014).
- [29] M. Belicka, S. Dubnicka, A. Z. Dubnickova and A. Liptaj, Phys. Rev. C **83**, 028201 (2011).
- [30] J. Qiu, talk presented at the KEK workshop on 'Hadron physics with high-momentum hadron beams at J-PARC', March 2015.